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COSMOS: MULTI-LAYERED NETWORK SURVIVABILITY PROJECT

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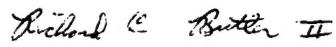
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COSMOS: MULTI-LAYERED NETWORK
SURVIVABILITY PROJECT

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CosMoS: Multi-Layered Network Survivability Project

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Abstract

A major attack can significantly reduce the capability to deliver services in large-scale networked information systems. In this project, we have addressed the survivability of large-scale heterogeneous information systems that consist of various services provided over multiple interconnected networks with different technologies. The communications network portions of such systems are referred to as multi-networks. We specifically address the issue of survivability due to physical attacks that destroy links and nodes in multi-networks. The end goal is to support critical services in the face of a major attack by making optimum use of network resources while minimizing network congestion. This is an area that is little studied, especially for large-scale heterogeneous systems. In this report, we present an overview of our contributions in this area.

1. Introduction

A major attack or a failure can significantly reduce the capability to deliver services in large-scale networked information systems. The drastic effects of communications network failures (even for non-malicious cases) have been demonstrated by several widely publicized network outages in recent years. We broadly classify any type of attack or failure broadly into two groups: physical attack/failure and software attacks. Physical attacks include attacks to destroy switches or transmission systems in some part of a network. Software attacks include attacks such as intruders breaking into systems and destroying, compromising and/or manipulating systems through software change (e.g., injecting false information into network routing tables). In this DARPA Project, our work addresses the first group of attacks, i.e., the physical attacks. The obvious question is how to build and evolve a network architecture to cope with any major physical attack so that critical information systems can still communicate by utilizing the available network and system resources. It may be noted that a major attack can be caused by a 'single' failure (such as an attack destroying a single high traffic link or node) or 'multiple' failures (such as an attack destroying multiple links and/or nodes). In the rest of the discussion, the term's "failure" and "attack" will be used interchangeably.

Most network-based information systems environments consist of a combination of legacy and emerging technologies. Broadly speaking, the environment can be classified into three layers. The top ("application/service") layer is where services such as voice, data, video, multi-cast video, and other distributed services are provided. These services are provided over the middle layer (referred to here as the "switched network layer") which consists of the networking environment such as circuit-switching, packet-switching (TCP/IP), ATM, and virtual private networks (for special services). Finally, the middle layer is provided over the network transmission environment layer (the bottom "physical" layer) which typically consists of a mixed technology infrastructure containing fiber and non-fiber wirebased systems as well as wireless components (microwave, cellular, satellite, etc.). Note that an application/service may traverse several interconnected networks with different physical layer and network layer components. For brevity, such heterogeneous multi-layered systems, which takes a resource-directed network architecture view, will be labeled as "*Multi-Networks*".

In this work, we address survivability to provide network design and management procedures towards minimizing the impact of failures on multi-networks. Survivability techniques can be classified into three categories: 1) prevention, 2) network design, and 3) traffic management and restoration. Prevention techniques focus primarily on improving component and system reliability. Some examples are the use of fault-tolerant hardware architecture in switch design, provision for backup power supplies and transmission equipment, use of frequency hopped spread spectrum techniques to prevent jamming in military radio networks and so on. Network design techniques try to mitigate the effects of system level failures such as link or node failures by placing sufficient diversity and capacity in the network topology. For example, the use of multi-homing nodes so that a single link failure cannot isolate a network node or an access network. Traffic management and restoration procedures seek to direct the network load such that a failure has minimum impact when it occurs and that connections affected by a failure are reconnected around the failure. Survivability goals may be accomplished by designing network infrastructures that are robust to malfunctions of nodes and links, and implementing network control systems that are inherently fault-tolerant and self-healing.

Given the multi-networks environment, survivability and restoration can be addressed at multiple levels. Although it may be possible to address survivability in each layer completely independently, our view is that a multi-layer coordinated and integrated survivability and restoration approach is most desirable to make maximum use of available resources. This should also take into account the underlying technology infrastructure so that evolving survivable network architectures can be generated. With this in mind, our goals in this project have been to address the following inter-related issues:

- Development of network design models/algorithms to provide a quality of service (QoS) specified under any failure condition. This work addresses the problem of intelligently designing and evolving a network topology architecture and configuration starting from an existing architecture and legacy networks to improve survivability.

- Development of network management algorithms (e.g., provisioning of backup routes, virtual circuit rerouting algorithms, etc.) which make optimum use of network resources after a failure (both single and multiple types) in support of critical services. This work concentrates on the design and analysis of multiple priority traffic restoration techniques to provide service continuity while minimizing the network congestion. The restoration algorithms will be suitable for automatic invocation by network components, resulting in a self-configuring system that adapts to the changing fault environment. Since emerging multi-casting services such as audio/video conferencing will be critical under an attack. We plan to address the issue of the survivability of multi-casting services.
- Emphasis on studying the transient network congestion that occurs after a failure and incorporating its effect into the design of the network and the traffic restoration algorithms. Thus, not only will a critical network user be provided service continuity, but the quality of the service can be provided in a graceful manner.
- Functional needs for the network management for multi-networks survivability and demonstration of some of the basic concepts and procedures through a proof-of-concept testbed implementation.

With the above goals in mind, we have divided the work into the following main components:

- Development of design models and tools for survivable networks.
- Development of simulation models and tools that can be used to study failures.
- Analysis of various network scenarios involving a failure using the tools developed, as well as an evaluation of traffic restoration algorithms.
- A network management framework development for multi-layered network survivability and its proof-of-concept implementation in the MIMIC (Mini Intelligent Multi-networks Information survivability Concepts) testbed at the University of Missouri–Kansas City.

In the rest of the document, we will visit each of these components. It is not possible to cover all of our publications and results in this overview paper. Thus, we summarize our contributions. As applicable, we have indicated the technical reports, theses and publications where more details can be found.

2. Network Design Models

In general, survivable network design refers to the incorporation of survivability strategies into the network design phase in order to mitigate the impact of a set of specific failure scenarios. Survivability is typically achieved through, either placing diversity and spare capacity in the network topology (or virtual topology) or adding redundancy to network components (e.g., 1+1 automatic protection switching). In

general, taking an approach of diversity and spare capacity placement by adopting a mesh type topology with extra capacity is known to be more cost effective and flexible (i.e., can respond to a wider range of failures), than following a redundancy approach. We are interested in network design models that include issues related to network survivability within the framework of the models. In this section, we describe some of the models and tools we have developed.

2.1. Survivable Virtual ATM Network Design

The details of this work are reported in the doctoral dissertation of R. Cotter[6]. In this section, we have highlighted the main contribution of this work.

In a multi-network environment, services required by the upper layer can be provided over a logical network. An example of such a logical network is an ATM-based (Asynchronous Transfer Mode-based) virtual network where virtual paths (VP) are defined for different services based on the demand requirement of the application services level. A critical requirement to address is the survivability of such networks, especially taking into consideration the dynamically rearrangeable capability of ATM VPs. In such an environment, to address for survivability, three different strategies are considered: redesign of the entire network for every possible failure scenario, design of the affected parts (VPs) for any failure scenario, and built-in diversity in the initial design of the network.

While addressing these strategies, along with issues such as consideration of multicast group traffic demand that needs to be survivable too, we have been able to develop a generic multi-commodity flow based optimization model that can capture them all very well. This is a major contribution in itself. Further, by looking at the structure of the problem, we have developed an algorithmic framework that can also be used for all of the strategies and scenarios. At the core of this algorithmic framework is a decomposition algorithm which is based on the duality-based subgradient optimization algorithm described in [14].

The design model has been implemented and tested on 96 different test networks ranging from 10-nodes in a network to 100-nodes in a network with multiple service classes and traffic load periods. In addition, a protocol message mechanism that works at the ATM VP level has also been developed. It was geared for ATM VP network survivability.

With the introduction of MPLS-based architecture, it appears that the model we have developed will be applicable in MPLS based networks too. This requires further work (not within the scope of the present project).

2.2. Book-ahead Guaranteed Survivable Services

In this work, we have considered a best-effort Internet environment with added capability to provide some guaranteed services that are requested ahead of time. An integral requirement for such guaranteed services may be some level of survivability. A possible approach here is to consider a pair of diverse paths for every survivable demand request. At the same time, to assign bandwidth on the back-up for survivability would mean that other best-effort services cannot access this bandwidth if there is *no* failure. Thus, this can lead to consideration of hard requirements and soft requirements.

In addition, such a problem can have conflicting goals. For example, (a) maximization of residual capacity for usage by best effort services, (b) minimization of the cost of the book-ahead survivable provisioning, and (c) possible penalty for not being able to provision for some requests. We have been able to develop an optimization formulation that captures such conflicting goals in a comprehensive manner.

We have done studies on several sample networks and demand requirements to show the effectiveness of the model in meeting different objectives. The details of the model and the results are reported in [23].

2.3. Survivable STM Network Design

STM refers to synchronous transfer mode. Networks based on SONET, and digital cross-connect systems fall under the STM category. In [1, 2], we consider the problem of given a STM mesh type network topology, the normal traffic demand, and the capacity allocation to meet the normal traffic demand, how much spare capacity should be provisioned and where should it be located in order for the network to tolerate a specified set of failure scenarios (e.g., loss of any single link). The term "mesh" does not imply that the network topology is a full mesh, but rather that the network nodes are at least two connected.

Specifically, we present a novel STM survivable network planning technique based on a genetic algorithm formulation of the spare capacity assignment problem for the case of path restoration with link disjoint routes. Genetic algorithms [7] have received considerable attention in recent years for use in solving various combinatorial optimization problems, including the solution of integer programming problems. Genetic algorithms (GA) are stochastic search techniques that mimic the survival of the fittest (or best) paradigm observed in nature.

Our design methodology consists of using the genetic algorithm approach to implement the concept that traffic flows which travel over disjoint routes may be able to share spare capacity on a backup path, since it is unlikely that more than one failure will occur simultaneously. Thus, our approach tries to reduce the cost of spare capacity needed for a particular fault tolerance requirement (e.g., full recovery from any single link failure) by finding a set of backup paths that enables the sharing of spare capacity, which results in reducing the total cost due to the nonlinear economy of scale of spare capacity cost.

The description of the proposed methodology is given in detail in [1, 2] along with a study of numerical results for a variety of network topologies, illustrating the application of the proposed genetic algorithm technique, guidelines for parameter selection and analysis of the computational complexity. Additionally, for the sake of comparison, numerical results for small networks are given for the standard integer programming approaches and a popular heuristic from the literature. It is shown that the GA algorithm is far more computationally efficient while providing near optimal results (2-7%).

3. Simulation Tools

Our interest in studying the effect of a failure on a network and the performance of any newly developed routing and restoration algorithms has led us to the development/enhancement of different simulation tools. Specifically, we have been interested in understanding the implications at the packet-level granularity in the best-effort Internet environment as well as connection/session level granularity in the case of emerging Integrated Services Architecture. Due to our varied interest, it became apparent that just one tool cannot fit every environment. Thus, this led us to the enhancement of the MaRS tool to create the new tool, MoMaRS, which is ideal for understanding packet-level implications due to a failure for multicasting environment. We have also developed extensions to ns simulator [33] for the unicast service environment that addresses fault tolerance. However, to address and understand the connection-level effect, we needed a tool that can simulate several thousand connections in a short period of time.

3.1. MoMaRS Tool

MoMaRS is a packet-level simulation tool. The new tool has been created by extending the MaRS tool[3]. MaRS has very good built-in unicast routing components as well as various service level workload components. Its original design allows the study of a link failure. Our interest was to consider multi-cast services and their performance under failure, and we are also interested in considering an environment that addresses Differentiated-Services Internet[4] and Integrated Services Internet[5].

With this in mind, we have made major enhancements to create the MoMaRS tool. In particular, the tool now has two multicast routing components: MKompella[12] and Multicast Shortest Path First (MSPF) routing protocols, as well as multicast workload components for one-to-many and many-to-many communications. We have further added priority based scheduling at the nodes (routers) for emulating a differentiated-services environment, and Resource reSerVation Protocol (RSVP) along with a classifier, a packet scheduler, and an admission controller to emulate the Integrated-Services environment. In addition, a new TCP component is added to allow a user to study interaction between TCP behavior and routing dynamics due to a failure. In particular, this environment allows us to study a single or multiple link failure. We are currently working on a user's manual for this tool and it is expected to be available soon.

3.2. MuSDyR Tool

While MoMaRS is a good tool for understanding packet level impact, it is not geared towards studying session or connection level issues for large-number of sessions/connections. Due to lack of an available tool that suits our needs, we have developed a new simulator called MuSDyR[17] (Multi-service Simulator with Dynamic Routing) for this purpose. MuSDyR is designed to consider connection-level impact along with flow/connection-level quality of service routing components. Due to our special interest in studying a network failure, this tool has been designed from the beginning with the capability to study a failure. In particular, it has a partial restoration capability, allowing the user to do staggered restoration after a failure. In addition, this tool has the capability to re-route a connection in the event of a failure. The tool can easily handle simulation of ten thousand simultaneous connections. To consider the fact that network traffic is non-stationary and changes with time, a dynamic traffic generation module has been included in this tool along with the stationary traffic generation module. In addition, this tool has the built-in capability for reservation-based multicast services.

3.3. Extensions to NS simulator

In order to study the effects of failures and evaluate survivability schemes on unicast services for various next generation Internet architectures, we have developed a simulation tool by extending the Network Simulator-NS (version 2) [33]. NS is widely used in the Internet research community. In order to simulate survivability schemes for unicast services, new modules were added to NS including an admission-control agent, a RSVP agent, a flow-routing agent, a resource agent and a fault-tolerant agent. The admission-control agent determines if a connection requesting QoS will be accepted based on the available resources. The RSVP agent will send reservation messages to setup or tear down the flow along the path given by a flow-routing agent. The flow-routing agent at each node maintains path information (set of candidate paths to other nodes) and routing information once the flow is set up. The candidate path set for each node pair is precomputed and loaded into the simulation before execution. Using the candidate path set, the flow-routing agent runs the path selection algorithm to find the path that

gives the minimum cost route. A resource agent at each node keeps track of resource levels at all ports. The simulation model is constructed so that all nodes share global information of resource levels. A fault-tolerant agent at each node incorporates the different restoration recovery schemes. Additional modifications to NS include changes to statistics gathering routines to permit the gathering of transient behavior across multiple simulation runs.

4. Some Results

Using simulations, various analyses can be done to understand the impact of a failure, as well as performance, when a new control scheme is introduced to alleviate any problems. In this section, we briefly discuss some preliminary results. We are currently conducting several studies that will be reported elsewhere.

4.1. Transient Behavior with Multicast Services

Using the MoMaRS tool, we have studied the transient network behavior of multicast and unicast connections in both differentiated-service and integrated-service capable Internet architectures under major link failure. Detailed results can be found in [18, 24, 25]. We briefly highlight some of the results here. Our results show that the performance of multicast routing protocol is essential in reducing the overall network utilization, thereby reducing the overall delay for all packets through efficient network utilization. The priority-based routing algorithm does provide QoS assurance for higher priority traffic. Figure 1 shows a dramatic decrease in the instantaneous delay and jitter for a selected multicast traffic stream when priority-based routing is employed. RSVP along with enhanced queuing and scheduling mechanisms can provide required QoS for real-time traffic in the network with link failure as well as without link failure. Figure 2 shows that in the RSVP-enabled environment, the delay and jitter of the multicast traffic during the failure period remains more or less the same as that during the pre-failure and link recovery periods. This is a very significant improvement in QoS for multicast traffic when compared with base simulations where RSVP is not employed. Simulation results using different routing protocols show that the ability of RSVP to re-establish the affected reserved paths due to network failure depends on the underlying routing protocol.

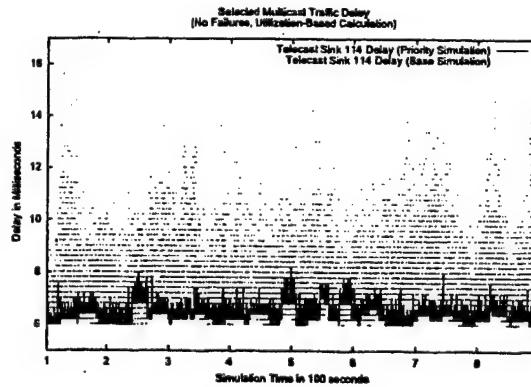


Figure 1. Telecast Sink 114 Instantaneous Delay (No Failure)

4.2. TCP Behavior due to Network Dynamics

Using the TCP component of the MoMaRS tool, we have also studied the impact of network dynamics on TCP[21, 22]. Network dynamics refers to the changes in the network state due to route oscillation, link failure and

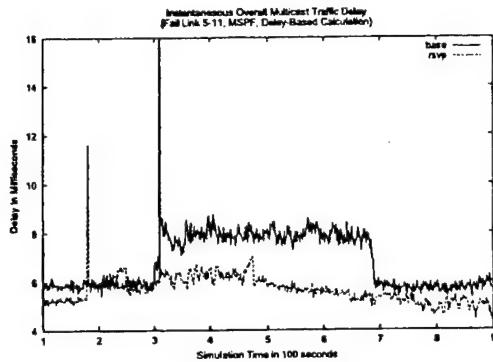


Figure 2. Multicast (Failure, MSPF, Delay-Based)

so on. While TCP has been extensively studied over the past decade, surprisingly, very little work has addressed the impact of network dynamics.

Our results show that the impact of network dynamics on TCP depends mainly on its acknowledging (or ACK-ing) behavior, where the performance of TCP with Non-Delayed acknowledgment (TCP-NDACK) is noticeably affected as compared with that of TCP with Delayed acknowledgment (TCP-DACK). During route oscillations, TCP flow displays asymmetry and false retransmission. Whereas during overlapping link failures, it displays multiple packet loss, retransmission timeouts, false retransmissions, and flow synchronization.

While false retransmissions can be eliminated in most of the cases by sharing congestion information between the header prediction and fast retransmit algorithm, an improved congestion detection mechanism at the nodes/routers and selective acknowledgement in TCP are necessary in order to handle link failures efficiently. We believe that a better acknowledgement technique would make TCP less susceptible and more adaptive to changes in network dynamics.

4.3. Survivable Services in NGI

In this work, we have investigated schemes for the survivability of guaranteed QoS connections that can be applicable in the Next Generation Internet (NGI) network architecture[30] using the extensions done to the ns tool. We assume the use of RSVP signaling to reserve resources along a fixed route (explicit path reservation) to provide QoS. A comparative study of the performance of two basic survivability schemes within an NGI architecture is presented. In the first scheme, a QoS connection is providing standby backup resources on a disjoint path by reserving resources on both the working and the backup path. In order to reduce the amount of backup resources required, a method for sharing backup resources when the working connections have disjoint routes has been included. In the second scheme, a dynamic search for restoration resources is conducted over a preplanned set of alternate paths upon notification of a failure.

A simulation based performance study was conducted to quantify the tradeoff in connection blocking from the guaranteed recovery scheme under normal operations versus the connection blocking after a failure from the dynamic search approach. In addition, the speed of recovery in reconnecting sessions is studied along with the transient network congestion produced by retransmission of lost data. The study shows that the first scheme results in much higher connection blocking under normal operations, faster restoration times, and longer transient congestion times due to non-optimal backup routing.

5. Traffic Restoration Procedures

As noted earlier, survivable traffic management and restoration procedures seek to direct the network load such that a failure has the minimal impact when it occurs, while the load affected by a failure is restored. The performance of a traffic restoration procedure will largely depend on the combination of the algorithm used for restoration and the spare capacity allocation in the network. In general, simple restoration schemes will lead to allocating more spare capacity, whereas more sophisticated restoration schemes will require less capacity, but may take a longer time to restore connections. In a multi-network environment we contend that distributed dynamic restoration schemes need to play a central role in traffic restoration since such networks will typically be operated by various service providers, possibly using different technologies at various network layers and the end-to-end spare capacity planning could be difficult. Our work on traffic restoration has concentrated on the development of algorithms for distributed dynamic traffic restoration to make optimum use of whatever resources are available after a failure, in support of critical services. Here, we summarize some of our main results from [9, 10, 34, 35].

5.1. Virtual Circuit Fault Recovery Routing

In [34] and earlier work, we have studied the problem of routing for traffic restoration after a failure in virtual circuit based wide area networks utilizing source node routing. Note that in such networks, a device failure will typically result in several nodes having many virtual circuits to restore and a critical issue in the restoration is the path chosen for rerouting. Another major factor on network performance after a failure in packet switched networks in general is the transient congestion period that results from restored virtual circuits attempting to send out the backlog of packets accumulated during the time delay between the failure occurring and restoration[32]. Standard routing algorithms in packet networks are normally based on minimizing the steady state network delay and such algorithms may be inappropriate for rerouting affected connections after a failure, since at this time, congestion is a paramount issue.

We present an optimization formulation of the rerouting problem by considering residual capacity in the network as well as the decision on whether or not to reconnect a disrupted virtual circuit[34]. Our formulation allows us to consider several routing schemes and fault scenarios in a unified framework. Note that after a failure, many virtual circuits will simultaneously need to be restored. Thus, we formulate the restoration problem as a bandwidth packing problem. Our formulation is based on precise information on the network link status and the decision is done in a centralized manner. In an actual implementation in a network, the source-node based routing makes the decision in a distributed manner, based on delayed information about network link status. We discuss how our proposed routing algorithms can be implemented in a distributed fashion.

The results of a simulation based performance study are reported, comparing the performance of both optimal centralized and distributed implementations of five different routing algorithms in terms of network congestion and traditional survivability metrics, such as the call blocking. Through extensive

simulation under different network load conditions, our results indicated that while traditional survivability metrics show little differences between the routing algorithms studied, the transient network congestion behavior is noticeably different. Further, it is shown that at low network loads, when there is enough spare resources so that restoration call blocking is low, the network behavior is the best when the load is evenly distributed throughout the network. In contrast, at heavy loads, when there are high amounts of restoration call blocking, one needs to match the routing scheme to the characteristics of the application to ensure the best network performance.

5.2. ATM Fault Recovery Priorities

In [9, 10], we propose a priority scheme for reconnection of virtual circuits (VCs) in ATM networks that have been disrupted by a failure. ATM networks offer several service categories each designed to handle applications with specific traffic characteristics. A failure typically results in *several* nodes being sources for failed virtual circuits with each having *many* virtual circuits in each service category to *simultaneously restore*, possibly on the order of tens of thousands. The way in which the virtual circuits are processed and routed will determine in part, if the connection is restored, the delay in reconnection and the QoS provided after restoration.

In [10], we have developed a restoration priority scheme based in part on the ATM service classes, which aims at minimizing the impact of a failure on the network while providing users the best possible service. The scheme involves both a priority for reconnection among ATM service classes and a rule for ordering and routing VCs within a service class. The proposed scheme is formulated within the context of switched VC routing but is applicable to virtual path restoration as well. The priority traffic restoration technique proposed is based in part on minimizing the number of dropped cells that need retransmission, thus reducing the transient congestion that occurs after restoration.

Numerical results evaluating the performance of the priority scheme show that it significantly reduces the amount of cells needing retransmission after a failure, thereby reducing network congestion at a cost of longer restoration times for lower priority virtual circuits. More recent work [9] formulates the priority restoration problem for ATM within a optimization framework and compares distributed implementations to the benchmark centralized optimization problem solution, suggesting some improvements to our original distributed scheme. This work clearly shows the benefits to both the high priority network user and the network operator in adopting a multi-priority restoration scheme, in terms of speeding up restoration and reducing network congestion.

5.3. Fault Tolerant Connection Oriented Multicasting

In [35] we examine the potential benefits of dedicated backup route(s) to provide survivability for ATM group communications. Specifically, we examine the feasibility of providing survivability using working multipoint routes with disjoint dedicated backup multipoint routes where the multipoint routes are setup using either Virtual Rings, shared multicast trees, or VC Mesh groups. We introduce an optimization formulation which identifies a “Disjoint Steiner Ring” within a general graph in order to construct Virtual Rings. Numerical results show that disjoint backup shared multicast trees and disjoint backup VC Mesh groups are not always available while self-healing Virtual Rings exist in all cases tested. In addition, experiments comparing the cost of providing survivability between self-healing Virtual Rings, shared trees, and VC Mesh groups show that self-healing Virtual Rings are lower in cost for the topologies considered.

6. Network Management Framework and Test-bed implementation

In the resource-directed layered network architecture, it may be noted that each layer will have independent policies regarding routing and resource management. However, the granularity and how often the routing changes are different. For example, in today's best-effort Internet, the routing can change at the packet level, while the routing in an ATM Network can be either at the connection or the virtual path level. In digital cross-connect networks, routing is either at the T1 or T3 level and does not tend to change in the scale of minutes or sometimes even days. When we consider the SONET environment, the routing can be at OC-3, OC-12 levels and so on. Further, the time scale of response of routing can be different for different environments. While SONET self-healing rings can reroute quickly (about 50 milliseconds), this is not the case in the SONET mesh network environment. Now, consider such a heterogeneous environment and assume that there are rerouting capabilities in each layer. Some important issues arise such as how a failure at the lower resource layer will affect the overall network, what is the best way for overall networks to respond to a failure, and what functionalities are needed for the failure management.

The administration and management of such a resource-directed multi-layered communication network involve some additional complexities in the routing and resource management strategies during link/node failure situations. Although the traditional management systems, which are designed to manage the network of single administrative domain or of homogeneous technology, do deal with issues related to resource management and survivability, the scope of the management information available to the domain-specific management systems is very localized. For example, the management system of a virtual private network may request an additional capacity on an overflowing point-to-point link. Similarly, a link failure at the physical layer may affect some of the virtual channels of service provider networks at the layers above the physical network. Currently most of these inter-domain issues are handled by human managers. However, with ever-growing multi-layered communications networks, it would be difficult for the human managers to handle the increasing number of such tasks. Another important factor is the desired reaction time for the inter-layer network management issues. For example, when a physical link fails, some of the affected logical channels require immediate attention so that at the user level, there will not be any perceivable breakdown of service.

One of the limitations of the domain-specific and technology specific management systems is that the abstraction of the management information is different from one domain to another. Also, each of these management systems will have no knowledge about the abstraction of management information of other domains. The interaction and exchange of management information among the domain-specific management systems are essential in the management systems of multi-layered networks. Hence, the definition of an interface of communication and a common abstraction of management information forms an important factor in the implementation of such management systems for multi-layered networks. The manager at an upper level of hierarchy uses different interfaces of communication to interact with different domain-specific managers at the lower level.

As a part of this project, we have developed a loosely-coupled hierarchical framework that can facilitate maximal survivability of services in multi-layered networks for various failure situations. More details about this work can be found in [11, 15, 26, 28]. In this discussion, we specifically consider a resource directed two-layered architecture where the networks at the upper layer are called 'user networks', while in the lower layer, we have a "provider network". We assume that user networks and the provider network are *not* all completely controlled by the same network administration. In each of the user network or the provider network, we assume that there is at least a domain-specific manager. In this framework, the domain-specific managers are called by the name of the domain for which they are responsible.

All the domain-specific managers will interact with domain independent managers in the upper level of hierarchy. This domain independent manager is called *Across Layer Manager of Managers (ALMoM)*. The communication interface between domain-specific managers and ALMoM specifies the management information that is exchanged and a messaging protocol required for the exchange of information. This architecture is designed to incorporate the management functionalities such as notification of link failures at the provider network and automated expansion of bandwidth of virtual links at the user network. The domain specific manager at the lower layer (provider network) will come to know of the physical link failures almost immediately, which may not be the case with domain-specific managers of upper layers (user networks). Depending on the network technology and the exchange due to the management protocol, the managers will realize the failure of logical virtual links (due to failure of physical link) with a certain amount of delay. In such cases, early notification of the link failure from the managers of the physical layer network is useful in initiating recovery mechanisms for affected links.

As a proof of concept, we have implemented our framework for the case of a two-layered network with an ATM network as the provider network and an IP network as the user network in the MIMIC testbed at the University of Missouri-Kansas City. Note that this platform is used for a low-cost proof-of-concept demonstration. The basic idea can be implemented in other environments, where the user network/provide network paradigm is applicable. In the IP network, we have used FreeBSD routers, while the ATM Network consists of Fore Systems's LE155 switches.

In our current implementation of ALMoM, the survivability mechanism is the only management functionality that is implemented. To make this implementation operating system and location independent, we have used a CORBA-based object management environment and Java programming language. With the CORBA based approach, we have modularized the management system not only at the component level, but also at the management

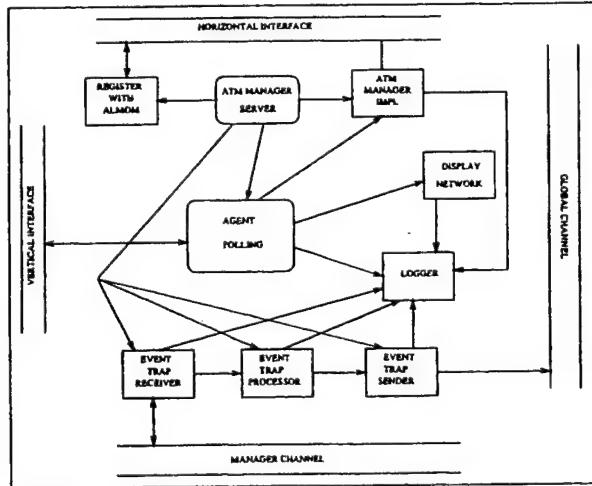


Figure 3. Implementation of the Domain-Specific Manager

functionality level. For example, the modular implementation of the manager component of the provider network is shown in Figure 3.

An important advantage of modular implementation is that new management functionalities can be added into each of the manager components without much modification to the rest of the implementation. Similarly, *EventChannel* service, which is readily available in the CORBA environment, is used for broadcasting critical events that may have been occurring in the network to various management components. Notably, a physical link failure is one such critical event. Depending on the size of the network, there can be more than one *EventChannel* active in the system. In this implementation, we have

used two channels, the manager channel and the global channel, providing broadcast service between technology-specific agents and domain-specific managers, and between domain-specific managers and ALMoM, respectively. Each of the events broadcasted in these channels contains enough information, such as event identification, time stamp, origin network and so on, in its header to uniquely identify the event.

7. What we have learned

Obviously, an important question is what have we learned through the execution of this project that can be of value to others.

7.1. Design Tools

The design tool development and implementation is a good example where the model development and implementation tool were somewhat intertwined. Thus, an important angle to keep in mind is the implementation should be flexible enough so that any change in the model can be accommodated in a shorter time cycle. The second issue is that the networking environment is rapidly changing, thus requiring the need to have a rapid prototyping environment along with flexibility to do model extension/fine-tuning – we didn't anticipate this to the extent the changes have occurred when we started the project. We believe this remains a challenging issue.

7.2. Simulation Tools

The development time to build a simulation model is found to be quite time consuming. The debugging of the logic is not easy either. This took us more time than we initially estimated. Further, collection of runs/results of different scenarios can start accumulating very fast, thus needing an environment to do scalable storage/information management. This also dictated that we really needed a better computing platform set-up for these sorts of non-anticipated development.

7.3. Testbed Implementation

We faced several issues with the testbed implementation.

First, determining the right software vendor platform (in our case, CORBA-based platform) along with the hardware can be quite time consuming. A significant amount of time was then spent on reaching the academic license agreements. Sometimes, even after that, we received a software version which was not compatible with other software components, causing further delay.

Second, we found that the switching software from the switch vendor was not flexible and scalable to allow us to develop our dynamic network configuration need for multi-layered survivability. Essentially, what this translates to is that switch vendors often have the myopic view of only looking at the element level needs rather than network level needs. For example, in one case, it required telneting to the switch as root to change the configuration. If a network consists of say, a hundred nodes, this causes a major scalability problem.

8. Technology Transfer

Recently, two companies have contacted us regarding our multi-layered network survivability concept implementation. We are currently pursuing a negotiation with these two companies to form a partnership to do technology transfer.

9. Acknowledgments

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10. Contributors

The work accomplished here would not have been possible without the involvement of various personnel and their dedicated effort. The overall effort at the University of Missouri was led by Deep Medhi while David Tipper took the lead at the University of Pittsburgh.

10.1. University of Missouri-Kansas City

Robert Cotter was instrumental in the development of the survivable virtual ATM network design models, algorithms, and the prototype tool; this is all reported in details in his recently completed Ph.D. dissertation [6].

Several graduate students have been involved in development of MoMaRS simulation tools. Before the project started, Samir Shah started working on the first enhancement to MaRS[3] to consider the multicast shortest path routing component [27]. Then, Gerald Rogers initiated the development of the MKompella multicast routing algorithm and priority-based routing to consider differentiated services environment (reported in his MS thesis [24]; also, see [25]); Suresh Muppala added the RSVP-component to this tool [18] while Ulka Ranadive added the TCP component as well as HTTP workload to this tool [21, 22]. Wen-Jung Hsin as the post-doctoral research associate co-ordinated overall effort related to MoMaRS as well as in the analysis of different network failure scenarios using MoMaRS. Vamsi Valluri and Chengning Lu are currently working on the next version of this tool.

MuSDyR [17] connection-level routing simulation tool to study a failure was designed and developed from scratch by Shishir Ramam, Shankar Subramaniam, and Joshi Sivasankar; their MS theses have reported various aspects of the tool as well as analysis results [20, 29, 31]. Currently, Aekkachai Rattanadilokchai, Loren Rard and Yiming Huang are working on the next version of this tool.

Mark Hieber is finishing up developing a study environment where MoMaRS is coupled with a lower layer network reconfiguration module to allow multi-layer survivability study. Brenda Groskinsky is developing a numerical differential equation model to analyze the impact of reconfigurability in a dynamic traffic environment [8].

The initial set up and testing of the MIMIC testbed, Fred Summa led the effort while Aanand Ramachandran conducted some of the initial testing [19]. In the next phase, when the multi-network management framework was developed and then implemented, Sanjay Jain, Deepa Shenoy and Mukunda Saddi were heavily involved and their contributions have been documented in their respective theses [11, 26, 28]. Currently, Kaushik Deka, Chetan Desai, Jane Zupan and Dijiang Huang are involved in the updated version of the testbed and the framework.

Finally, Post-doctoral fellow T. Srinivasa Rao and Research Associate Wen-Jung Hsin have been key players who plunged into several aspects of the project, specifically new optimization model development, simulation analysis and in the test-bed implementation while Fred Summa has managed to bring sanity to the project by making sure that we have a working environment.

10.2. University of Pittsburgh

Several individuals have contributed to this project at the University of Pittsburgh. In particular Adel Al-Rumaih developed the genetic algorithm based spare capacity planning method and its implementation into a design tool in his Ph.D. dissertation [1]. Graduate student Yu Liu has contributed to the relative comparison study of the genetic algorithm approach and mathematical programming techniques reported in [2]. Ph.D. candidate Anotai Srikitja developed the extended version of the NS simulator and conducted the study on survivable service in NGI reported in [30]. Graduate student Wei-Ping Wang has contributed to the development of fault recovery routing algorithms reported in [34]. Ph.D. candidate William Yurcik developed the survivable ring approach to providing fault tolerant group communications detailed in [35] and his forthcoming Ph.D. dissertation. Visiting scholar Bjorn Jager has contributed to the development of fault recovery routing algorithms and priority restoration schemes as detailed in [34, 10] and his forthcoming doctoral dissertation [9].

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